Severe Particulate Pollution in Lanzhou China

Peter C. Chu*

Naval Ocean-Atmospheric Prediction Laboratory, Naval Postgraduate School, Monterey, California, USA

Yuchun Chen, Shihua Lu, Zhenchao Li

Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China

Yaqiong Lu

Department of Atmospheric Science, Chengdu University Of Information Technology, Chengdu, China

*Corresponding author: Tel: +1-831-656-3688; Fax: +1-831-656-3686; E-mail address: pcchu@nps.edu
URL: http//www.oc.nps.navy.mil/~chu

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Severe Particulate Pollution in Lanzhou China**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School,Department of Oceanography,Monterey,CA,93943**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**37**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Abstract

Concentrations of total suspended particles (TSP) and PM_{10} in Lanzhou China have been kept high for the past two decades. During intensive observational period from October 1999 to April 2001, the concentrations of TSP and PM_{10} are even increasing and becoming major air pollutants; the temporally total mean PM_{10} concentration is 2.56 mg m^{-3}. The rate of PM_{10} polluted-day occurrence to is 71% in a year, 89% in the winter, and 79% in the spring. Starting from November, the PM_{10} pollution intensifies, and reaches mid to high alert level of air pollution, continues until April next year, and is at low alert level in the summer. The temporally total mean TSP concentration is 5.92 mg m^{-3}. In the winter and spring, the TSP concentration is 2-10 times higher than the third-level criterion of air quality (severe pollution). Intrinsic factors (sources of pollution) and exterior preconditions (propagation of dust storms) for severe PM_{10} and TSP pollution are investigated.

Key words: Particulate pollutants, dust storm, air quality monitoring system, air pollution index, TSP concentration, PM_{10} concentration

1. Introduction

Lanzhou is located at a narrow (2-8 km width), long (40-km), NW-SE oriented valley basin (elevation: 1,500-m to 1,600-m) with the Tibetan plateau in the west, Baita mountain (above 1,700-m elevation) in the north, and the Gaolan mountain (above 1,900-m elevation) in the south (Fig. 1a). The Yellow River runs through the city from the west to the east.

Lanzhou has four districts (Fig. 1b): Chengguan, Qilihe, Xigu, and Anning. Chengguan (District-I), located in the eastern valley, is the metropolitan area including government, commerce, culture, and residence. Xigu (District-III), located in the western valley, is the large heavy industrial area. Qilihe (District-II), located in the middle valley, and Anning (District-IV), located in the north middle valley, are the mixed residential, small factories, and farming (vegetables) area. The heavy industrial includes petrol-chemistry, metallurgy, and mechanical manufacturing. Coal is the most important energy source, followed by gasoline and natural gas. Lots of smoke and ashes are emitted all the time both from the boilers and chimneys of plants and enterprises as well as residence. Generally speaking, the particulate pollution is heavier in winter than in summer.

The topographic characteristics make Lanzhou vulnerable to the invasion of dust storms (Fig. 1b). The aspect ratio of the valley (depth versus width) is around 0.07, which blocks the air streams due to the large frictional forces and causes weak winds and stable stratification (even inversion) to inhibit turbulent diffusion. The meteorological conditions (low winds, stable stratification especially inversion) cause the pollutants difficult to disperse. These conditions make Lanzhou one of the most polluted cities in China (Fig. 1c).

Annual and daily mean air quality standards for urban areas generated by the State Environmental Protection Agency (SEPA) are used as the air quality criteria. The second-level and third-level criteria for annual mean (TSP, PM_{10}) are (0.2, 0.10 mg m^{-3}), (0.3, 0.15 mg m^{-3}) (Table 1). The second-level and third-level criteria for daily mean (TSP, PM_{10}) are (0.3, 0.15 mg m^{-3}), (0.5, 0.25 mg m^{-3}) (Table 2). In Lanzhou, SEPA alerts the commercial and residential regions as the pollutants reach the second-level criteria and alerts the industrial regions as the pollutants reach the third-level criteria. In this study, the severe particulate pollutants (TSP and PM_{10}) in Lanzhou are identified.

2. Pollutant Concentration

An air-quality monitoring system has been established in Lanzhou with multiple sampling and sufficient numbers of stations. This is the part of the project entitled Air Pollution and Control in Lanzhou (APCL), supported jointly by Gansu Province and the Chinese Academy of Sciences and carried out from 1999 to 2001. In this study, detail analyses are conducted on the TSP and PM_{10} concentration data collected by the air-quality monitoring system as well as the associated meteorological conditions. The objectives are to detect detailed temporal and spatial variability of TSP and PM_{10}, to evaluate the air-quality objectively and quantitatively, to analyze the pollutant sources, and to find the favorable meteorological conditions for the pollutant dispersion.

The data are from several sources: the APCL project, routine air-quality observations, and routine meteorological observations. From the APCL project, the air quality data were collected at observational stations (St-1 - St-5) from October 1999 to April 2001 and at observational stations (St-6 - St-8) from August 2000 to April 2001.

The station-5 (Yuzhong), located in countryside, is taken as the reference station (Fig. 1b). Over these stations, daily TSP concentration is calculated.

The total temporally mean TSP concentration exceeds the third-level annual mean TSP concentration criterion (0.3 mg m^{-3}) for all stations except for the background station (St-5: 0.28 mg m^{-3}) (Table 3). Among them, (St-1, St-3, St-4) have (0.69, 0.74, 0.68) mg m^{-3}, which are twice larger than the third level annual-mean standard (0.3 mg m^{-3}). Even at the reference station (St-5), the annual mean TSP concentration (0.28 mg m^{-3}) is quite close to the third-level national criterion (0.30 mg m^{-3}) (comparison between Table 3 and Table 1).

The daily PM_{10} concentration was collected continuously from the routine air-quality observations by SEPA in Lanzhou from June 2000 to May 2001 (station-E in Fig. 1b). Fig. 2 shows the temporal variation of daily mean TSP concentration at four APCL stations (St-1, St-3, St-4, and St-7) to represent District-I, District-II, District-III, and District-IV, respectively. The daily mean TSP concentration is larger than the second-level criterion (0.3 mg m^{-3}) almost all the time and than the third-level criterion (0.5 mg m^{-3}) sometimes. Fig. 3 shows the temporal variation of daily mean PM_{10} concentration at station-E. From June 2000 to May 2001, the daily mean PM_{10} concentration often exceeds the second level criterion (0.15 mg m^{-3}) and even the third-level criterion (0.25 mg m^{-3}) especially in winter and spring. Besides, the TSP (Fig. 2) and PM_{10} (Fig. 3) concentrations have increasing trends from November 2000 to April 2001.

Fig. 4 shows the monthly mean, minimum, and maximum TSP concentration (mg m^{-3}) at the eight ACPL stations. The horizontal dashed and solid lines are referred to as

the second and third level criterions for daily mean concentrations (Table 2). The monthly mean TSP concentration exceeds the second-level daily mean TSP standard (0.3 mg m^{-3}) all the time at all the ACPL stations in the urban area of Lanzhou. Even in the reference station (St-5) located in the countryside, the monthly mean TSP concentration often exceeds the second-level daily mean TSP criterion. The monthly maximum TSP concentration in the reference station (St-5) always exceeds the second-level daily mean TSP criterion and even exceeds the third-level daily mean TSP criterion (1.0 mg m^{-3}) quite often. At the seven urban ACPL stations, the monthly maximum TSP concentration often exceeds the third-level daily mean TSP criterion.

Taking March 2001 as an example, the monthly mean TSP concentration is 4-6 times larger than the monthly mean third-level criterion (0.3 mg m^{-3}). Even in the reference station (St-5), the observed monthly mean TSP concentration is 1.21 mg m^{-3}, which is more than 4 times of the third-level criterion (Table 4). The monthly maximum TSP concentration is more than six times higher than the daily mean third-level criterion (0.5 mg m^{-3}) in all the eight stations. The monthly minimum TSP concentration is higher than the daily mean third-level criterion (0.5 mg m^{-3}) in most stations except the reference station (St-5, 0.25 mg m^{-3}) and St-8 (0.46 mg m^{-3}). The monthly mean PM_{10} (0.39 mg m^{-3}) is also much higher than its third-level criterion (0.15 mg m^{-3}).

The TSP concentration has an increasing tendency (Fig. 4). Among the eight ACPL stations, five stations (St-1 to St-5) have two years' data. To filter out the seasonal effect, the monthly mean TSP concentrations (mg m^{-3}) of the same month between period-1 (October 1999 - April 2000) and period-2 (October 2000 - April 2001) are compared at the four stations (Table 5). The monthly mean TSP concentration is more in

period-2 than in period-1 all the time. The monthly maximum TSP concentration is more in period-2 than in period-1 almost all the time except three occasions (marked '*' in Table 5). The monthly mean PM_{10} concentration exceeds the second level criterion all the time (Table 6).

3. Air Pollution Index

Air pollution index (API) is a quantitative measure for uniformly reporting the air quality for different constituents and connects to the human health. SEPA classifies the air quality standards into 5 major categories due to API values (Table 7): I (clean), II (good), III (low-level pollution), IV (mid-level pollution), and V (high-level pollution). The categories III and IV have two sub-categories: (III_1, III_2) and (IV_1, IV_2).

Daily mean API of PM_{10} at St-E (Fig. 5) shows severe PM_{10} pollution during the observational period from June 2000 to May 2001. API for PM_{10} changes drastically and has large values (more than 500) in almost all seasons such as summer (June 13 and July 27, 2000) and winter (December 2000 to January 2001). API for PM_{10} is usually below 200 from August to October 2000. It increases drastically in November 2000, and keeps high values (200-600, categories IV and V) until April, 2001.

Monthly mean API for TSP is large even in the background station (St-5) with the value larger than 200 during April-May 2000 and January-April 2001 (Fig. 6). It is always greater than 200 during the whole observational period at St-4 with a maximum value above 600 in March 2001. At the other stations, it is generally greater than 200 (but always larger than 100) during the period except in summer 2000. March 2001 is one of the severely polluted months of TSP (Table 8). The maximum API for TSP at all eight

stations is greater than 500. The monthly mean API of TSP is greater than 500 in all the city stations with 400 in the background station (St-5).

Monthly mean API of PM_{10} is larger than 200 and the maximum API of PM_{10} is larger than 500 during November 2000 to April 2001 (except maximum API = 464 in December 2000) (Table 9). During the other period, the monthly mean API of PM_{10} is equal to or less than 126, but the maximum API of PM_{10} is still large such as greater than 500 in June 2000, 467 in July 2000, and 356 in May 2001. This indicates the intermittent feature of the PM_{10} pollution events.

4. Long Term Trend

Fig. 7 shows the evolution of annual mean TSP concentration measured at the local SEPA station (103.631^{o}E, 36.103^{o}N), which is marked as the solid circle in Fig. 1b. The annual mean TSP concentration is always above the third level standard: 0.3 mg m^{-3}. The second-level and third-level criteria of the annual mean of TSP are represented by dotted-dashed and dotted horizontal lines. The annual mean concentrations of TSP is higher than the third level standard (0.3 mg m^{-3}) all the time from 1988 to 2000 and keeps quite steady with time (does not have an decreasing trend).

5. Occurrence Rate

Table 10 shows the TSP observational days, the days with the API of TSP between 201 to 300 and greater than 300 during a month, and the occurrence rate of severe TSP alert, which is the ratio between the days with API of TSP greater than 200 and the total days of observation. Monthly mean API of TSP is larger than 200 almost all the time in winter and spring (Table 10) with some months even exceeding 300, such as in December 1999, December 2000 for St-3, in January, March 2001 for St-1, and in

March 2001 for St-4 and St-7, where the API of TSP exceeds 300 all the time. According to Table 7, the TSP pollution in Lanzhou often reaches middle to high levels of pollution (categories IV and V).

The high-level TSP pollution (API > 300, category V) occurs frequently except summer (Table 11): 68% in the spring, 16% in the summer, 45% in the fall, and 63% in the winter. The occurrence rate of TSP pollution is usually smaller for mid and low levels than for the high level. For example, the low level pollution (100 < API ≤ 150, category III) occurs at 5% in the spring, 26% in the summer, 14% in fall, and 7% in the winter.

Although the high-level PM_{10} pollution (API > 300, category V) occurs less frequently (Table 12) than that of TSP, it is still quite often in spring (25%) and winter (32%). The occurrence rate of PM_{10} pollution is usually larger for mid and low levels than for the high level. For example, the low level pollution (100 < API ≤ 150, category III) occurs at 22% in spring, 45% in summer, 30% in fall, and 22% in winter.

6. Local and Remote Sources

6.1. Local Emission Rate

Fig. 8 shows the spatial distribution of annual particulate pollutant emission rate per square kilometer (unit: 0.1×10^4 kg km^{-2} yr^{-1}) in 2000. Emission rate is the largest in District-III, mainly from industrial sources (indicated with underlines in Fig. 8), for instance, annual emission rates are 693.5×10^4 kg km^{-2} yr^{-1} from the Chemical Plant of Lanzhou and 573×10^4 kg km^{-2} yr^{-1} from the Electric Power Plant of Xigu (District-III). However, the total pollutant emission in Lanzhou is 4020.7×10^4 kg in 1999, and 3578.2×10^4 kg in 2000. From 1999 to 2000, it decreases 442.5×10^4 kg. Although the local emission rate has been reduced, the TSP concentration is still high.

6.2. Remote Source – Dust Storms

Recent studies indicate that dust storms originated in the East Asia not only influence air pollution in the origins and their neighboring regions [Uno et al, 2001; Murayama et al., 2001; Sun et al., 2001; Zhou et al., 2002], but also have a long-distance effect across Pacific by atmospheric circulation [Husar et al., 2001; Tratt et al., 2001; Sun et al., 2001; Laat et al., 2001; Clarke et al., 2001]. The major sources of the dust storms are the Gobi desert in Mongolia and northern China and Taklimakan desert in western China [Sun et al., 2001]. In April 1998, an Asian dust storm proceeded eastward with the west wind across Pacific Ocean and subsided to the surface along the mountain ranges between British Columbia and California [Husar et al., 2001; Tratt et al., 2001; Vaughan et al., 2001]. Other reports indicated that there is a positive correlation between dust storm in Hexi Corridor and air pollution in Lanzhou [Wang et al., 1999; Ding et al., 2001]. As one of the major cities in northwest China, and the capital of Gansu Province, Lanzhou suffers greatly from the dust storms [Wang et al., 1999; Ding et al., 2001]. The particulate pollution in Lanzhou has been on the top among all cities in China.

With limited observations, several studies show the favorable meteorological condition for air pollution of Lanzhou such as inversion or stable stratification that suppresses atmospheric turbulence transfer [Hu and Zhang, 1999; Lu et al., 2001;Chen et al, 2001; Zhang, 2001]. In addition, Shang et al. [2001] show significant correlation between static stability and concentrations of SO_2, CO, and NO_x. Wang et al., [1999] and Ding et al. [2001] obtain positive correlation between dust storm occurrence in Hexi Corridor and the particulate pollution in Lanzhou.

As described in Section 5, TSP and PM_{10} are the most series pollutant in Lanzhou. Occurrence of high TSP and PM_{10} concentrations are associated with the propagation of dust storms. From Fig. 9 (January 2001) to Fig. 12 (April 2001), the daily TSP concentrations at the background station (St-5) and spatially averaged over seven (St-1 to St-4 and St-6 to St-8) city stations are illustrated in panel-a, and the daily PM_{10} concentration at St-E is shown in panel-b. On the two panels the dust-storm is marked by the symbol '$S\!\!\!\rightarrow$'. Dust-storms occur quite often in the vicinity of Lanzhou (Table 13): 9 days in January 2001, 3 days in February 2001, 9 days in March 2001, and 12 days in April 2001. For example, during the dust-storm from December 31, 2000 to January 1, 2001, dusts float in the sky for 7 days (January 1-5, 2001) [Ding et al., 2001], and causes high TSP and PM_{10} concentrations on January 1, 2001 (TSP: 3.08 mg m^{-3} and PM_{10}: 2.56 mg m^{-3}) and on January 2, 2001 (TSP: 1.75 mg m^{-3} and PM_{10}: 2.01 mg m^{-3}) as shown in Fig. 9.

Deserts and barren lands are widespread in the northwest of China and they are expanding attributing to underdeveloped methods of producing and management, and irrational utilization of resources. Aridness and desertization cause frequent dust storms [Dong et al., 1999; Wang and Cheng, 1999]. Thick dots in panel-c of Fig. 9 to Fig. 12 represent the meteorological stations where the dust storms were reported. The dust storms that directly cause severe particulate pollution of Lanzhou are mainly generated in neighboring regions such as Hexi Corridor (Fig.1a marked by G1, G2, G3), Badanjilin desert (100^{o}~103°E, 39^{o}~42°N, centered at C1), south of Tenggeli desert (103^{o}~106°E, 37^{o}~39°N, centered at C2), and Caidam desert (about 92^{o}~98°E, 36^{o}~38°N, centered at C3). These regions are enclosed as a ladder-shaped region (Fig 1a). When the air is dry,

strong winds blowing over the deserts cause the dust-storms and in turn brings high TSP and PM_{10} concentrations in Lanzhou.

8. Conclusions

(1) TSP pollution is very series in Lanzhou with 2~10 times greater than the third level standard in winter and spring. March 2001 is the most severely polluted month with API＞500 all the time. The high-level TSP pollution (API > 300, category V) occurs frequently with 68% in spring, 16% in summer, 45% in fall, and 63% in winter.

(2) The PM_{10} pollution is also quite high in Lanzhou with the high-level pollution (API > 300, category V) occurring quite often in spring (25%) and winter (32%). The occurrence rate of PM_{10} pollution is usually larger for mid and low levels than for the high level. For example, the low level pollution ($100 < API \le 150$, category III) occurs at 22% in spring, 45% in summer, 30% in fall, and 22% in winter.

(3) Dust-storms occur quite often in the vicinity of Lanzhou (9 days in January 2001, 3 days in February 2001, 9 days in March 2001, and 12 days in April 2001), and cause high TSP and PM_{10} concentrations in Lanzhou. The maximum TSP concentration was observed as 5.29 kg m^{-3} (March 2001). Reduction of the TSP and PM_{10} concentrations is an urgent issue for air quality control in Lanzhou and related to the reduction of dust storms in the vicinity. This may be achieved by the improvement of the land surface characteristics such as long term forestation and vegetation.

Acknowledgments

This work was jointly supported by the National Natural Science Foundation of China Major Programs No. 40305020, and the Naval Postgraduate School of USA. The authors wish to thank Prof. J. Wang for invaluable comments. The data for this study are

provided by the program entitled "Air Pollution and Control in Lanzhou" jointly sponsored by the local government of Gansu Province and the Chinese Academy of Science.

References

Chen, Y. C., X. Q. An, and S. H. Lu, 2001. Precautionary strategy of the influence of afforestation on air pollution in Lanzhou. Plateau Meteorol., 20 (Suppl.), 126-132 (in Chinese with English abstract).

Chu, P.C., Y. Chen, and S.H. Lu, 2004. Afforestation for valley urban air quality improvement. Proc. Fifth Symposium on Urban Environment, Amer. Meteorol. Soc., Vancouver, August 23-27, pp. 7 (in CD-Rom).

Clarke, A. D., W. G. Collins, P. J. Rasch, V. N. Kapustin, K. Moore, S. Howell, and H. E. Fuelberg, 2001. Dust and pollution transport on global scales: Aerosol measurements and model predictions. J. Geophys. Res., 106, D23, 32555-32569 (2000JD900842).

Ding, R. Q., D. B. Yang, S. G. Wang, K. Z. Shang, and J. H. Li, 2001. The effect of sandstorm on air pollution over Lanzhou city. Plateau Meteorol., 20 (Suppl.), 104-109 (in Chinese with English abstract).

Dong, G. R., B. Wu, L. J. Ci, H. S. Zhou, Q. Lu, and B. Luo, 1999. Present situation, cause and control way of desertification in China. J. Desert Res., 19 (4), 318-332 (in Chinese with English abstract).

Husar R. B., D. M. Tratt, B. A. Schichtel, S. R. Falke, F. Li, D. Jaffe, S. Gassó, T. Gill, N. S. Laulainen, F. Lu, M. C. Reheis, Y. Chun, D. Westphal, B. N. Holben, C. Gueymard, I. McKendry, N. Kuring, G. C. Feldman, C. McClain, R. J. Frouin, J. Merrill, D. DuBois, F. Vignola, T. Murayama, S. Nickovic, W. E. Wilson, K. Sassen, N. Sugimoto, and W. C. Malm, 2001. Asian dust events of April 1998. J. Geophys. Res., 106, D16, 18317-18330 (2000JD900788).

Hu Y. Q., and Q. Zhang, 1999. Atmosphere pollution mechanism along with prevention and cure countermeasure of the Lanzhou hollow basin, China Environ. Sci., 19 (2), 119-122 (in Chinese with English abstract).

Laat, A. T. J., J. Lelieveld, G. J. Roelofs, R. R. Dickerson, and J. M. Lobert, 2001. Source analysis of carbon monoxide pollution during INDOEX 1999. J. Geophys. Res., 106, D22, 28481-28495 (2000JD900769).

Lu, S. H., Y. C. Chen, and X. Q. An, 2001. Numerical simulation of local circumfluence and inversion of Lanzhou, Plateau Meteorol., 20 (Suppl.), 1-7 (in Chinese with English abstract).

Murayama, T., N. Sugimoto, I. Uno, K. Kinoshita, K. Aoki, N. Hagiwara, Z. Liu, I. Matsui, T. Sakai, T. Shibata, K. Arao, B.-J. Sohn, J.-G. Won, S.-C. Yoon, T. Li, J. Zhou, H. Hu, M. Abo, K. Iokibe, R. Koga, and Y. Iwasaka, 2001. Ground-based network observation of Asian dust events of April 1998 in east Asia. J. Geophys. Res*.,* 106, D16, 18345-18359 (2000JD900554).

Shang K. Z., C. Y. Da, Y. Z. Fu, S. G. Wang, and D. B. Yang, 2001. The Stable Energy in Lanzhou city and the Relations between Air Pollution and It. Plateau Meteorol., 20 (1), 76-81 (in Chinese with English abstract).

Sun, J. M., M. Y. Zhang, and T. S. Liu, 2001. Spatial and temporal characteristics of dust storms in China and its surrounding regions, 1960-1999: Relations to source area and climate, J. Geophys. Res*.,* 106*,* D10, 10325-10333 (2000JD900665).

Tratt, D. M., R. J. Frouin, and D. L. Westphal, 2001. April 1998 Asian dust event: A southern California perspective J. Geophys. Res*.,* 106, D16, 18371-18379 (2000JD900758).

Uno, I., H. Amano, S. Emori, K. Kinoshita, I. Matsui, and N. Sugimoto, 2001. Trans-Pacific yellow sand transport observed in April 1998: A numerical simulation, *J. Geophys. Res.,* **106***,* D16, 18331-18344 (2000JD900748), 2001.

Vaughan, J. K., C. Claiborn, and D. Finn, 2001. April 1998 Asian dust event over the Columbia Plateau. J. Geophys. Res., 106 , D16 , 18381-18402 (2000JD900751).

Wang, G. X., and G. D. Cheng, 1999. Land desertification status and developing trend in the Heihe River basin, *Journal of Desert Research*, 19(4), 368-374 (in Chinese with English abstract).

Wang, S. G., M. Yang, B. Qi, C. L. Xin, and M. F. Yang, 1999. Influence of Sand-dust Storms Occurring over the Gansu Hexi District on the Air Pollution in Lanzhou City, *J. Desert Res.*, 19 (4), 354-358 (in Chinese with English abstract).

Zhang, Q., 2001. The influence of terrain and inversion layer on pollutant transfer over Lanzhou city. China Environ. Sci*.,* 21 (3), 230-234 (in Chinese with English abstract).

Zhou, J., G. M. Yu, C. J. Jin, F. Qi, D. Liu, H. L. Hu, Z. B. Gong, G. Y. Shi, T. Nakajima, and T. Takamura, 2002. Lidar observations of Asian dust over Hefei, China, in spring 2000. J. Geophys. Res*.,* 107, 15, 4252, doi: 10.1029/2001JD000802.

Table Legends

Table 1. Air quality standards for annual mean particulate pollutant concentrations (mg m^{-3}) from the Chinese National Environmental Protection Agency.

Table 2. Air quality standards for daily mean particulate pollutant concentrations (mg m^{-3}) from the Chinese National Environmental Protection Agency.

Table 3. Location of observational stations and total temporally mean TSP concentrations (mg m^{-3}). Note that the second-level annual mean criterion of TSP concentration is 0.20 mg m^{-3}.

Table 4. TSP and PM_{10} concentration (mg m^{-3}) in March 2001.

Table 5. Comparison of TSP concentration (mg m^{-3}) between periods of October 1999-April 2000 and of October 2000 -April 2001.

Table 6. Monthly mean and maximum PM_{10} concentrations (mg m^{-3}) from June 2000 to May 2001.

Table 7. API and air quality management in China.

Table 8. Monthly mean, maximum, and minimum API of TSP in March 2001.

Table 9. Monthly mean and maximum API of PM_{10} from June 2000 to May 2001.

Table 10. TSP observational days, the days with the API of TSP between 201 to 300 and greater than 300 during a month, and the occurrence rate of severe TSP alert, which is the ratio between the days with API of TSP greater than 200 and the total days of observation. The symbol '-' is referred to no-observational data.

Table 11. Occurrence rate (%) of different levels of TSP pollution.

Table 12. Occurrence rate (%) of different levels of PM_{10} pollution.

Table 13. Dust storm statistics in Gansu Province from December 2000 to April 2001.

Figure Legends

Figure 1: Lanzhou: (a) geography, (b) topography, and (c) LANDSAT-TM imagery representing air pollution on 3 January 2001.

Figure 2. Daily mean TSP concentrations (mg m^{-3}) at: (a) St-1 (District-I), (b) St-3 (District-II), (c) St-4 (District-III), and (d) St-7 (District-IV)). Horizontal dashed line is daily mean second-level criterion (0.2 mg m^{-3}), while horizontal solid line is daily mean third-level criterion. Note that the daily mean TSP concentration is usually above the second-level criterion (0.3 mg m^{-3}).

Figure 3. Daily mean PM_{10} concentration at station-E. Horizontal dashed line is the daily mean second-level criterion (0.2 mg m^{-3}), while horizontal solid line is the daily mean third-level criterion (0.3 mg m^{-3}).

Figure 4. Monthly mean, maximum, and minimum TSP concentrations (mg m^{-3}) at St-1 to St-8.

Figure 5. Daily mean API of PM_{10} at station-E.

Figure 6. Monthly mean API of TSP at St-1 to St-8.

Figure 7. Annual mean TSP concentration (mg m^{-3}) measured at the SEPA station (103.631°E, 36.103°N), which is marked as the solid circle in Fig. 1b. The second-level criterion (0.2 mg m^{-3}) is represented by the horizontal dash-dotted line and the third-level criterion (0.3 mg m^{-3}) is represented by the horizontal dotted line.

Figure 8. Spatial distribution of annual particulate pollutant emission rate per square kilometer (unit: 0.1×10^4 kg km^{-2} yr^{-1}) in 2000. Here, the industrial sources are indicated with underlines; high-level sources are represented by the enclosed solid curves marked as 'H'. The dashed contours are topography (unit: m).

Figure 9. Daily mean (a) TSP, (b) PM_{10} concentrations (dust storm represented by the symbol '$\mathrm{S}\!\!\!\rightarrow$') in January 2001, and (c) horizontal distribution of dust storms (solid dots) in January 2001.

Figure 10. Same as Figure 9 except for February 2001.

Figure 11 Same as Figure 9 except for March 2001.

Figure 12. Same as Figure 9 except for April 2001.

Table 1. Air quality standards for annual mean particulate pollutant concentrations (mg m^{-3}) from the Chinese National Environmental Protection Agency.

Level of Criterion	TSP	PM_{10}
1	0.08	0.04
2	0.2	0.10
3	0.3	0.15

Table 2. Air quality standards for daily mean particulate pollutant concentrations (mg m^{-3}) from the Chinese National Environmental Protection Agency.

Level of Criterion	TSP	PM_{10}
1	0.12	0.05
2	0.3	0.15
3	0.5	0.25

Table 3. Location of observational stations and total temporally mean TSP concentrations (mg m^{-3}). Note that the second-level annual mean criterion of TSP concentration is 0.20 mg m^{-3}.

Site	Longitude E	Latitude N	Height Above Surface (m)	Region	TSP
St-1	103.84	36.04	25	Chengguan (District-1)	0.69
St-2	103.84	36.07	11	Chengguan (District-1)	0.57
St-3	103.71	36.08	15	Qilihe (District-3)	0.74
St-4	103.63	36.10	22	Xigu (District-2)	0.68
St-5	104.09	35.84	4	Yuzhong County	0.28
St-6	103.92	36.04	19	Chengguan (District-1)	0.56
St-7	103.74	36.10	15	Anning (District-4)	0.52
St-8	103.63	36.09	4	Xigu (District-2)	0.54

Table 4. TSP and PM_{10} concentration (mg m^{-3}) in March 2001.

	St-1 TSP	St-2 TSP	St-3 TSP	St-4 TSP	St-5 TSP	St-6 TSP	St-7 TSP	St-8 TSP	St-E PM_{10}
Max	3.96	3.98	4.21	3.08	5.29	3.15	3.84	3.75	1.12
Min	0.77	0.74	0.51	0.64	0.25	0.55	0.79	0.46	0.19
Mean	1.76	1.74	1.77	1.55	1.21	1.45	1.57	1.51	0.39

Table 5. Comparison of TSP concentration (mg m^{-3}) between periods of October 1999-April 2000 and of October 2000 -April 2001.

		October		November		December		January		February		March		April	
		1999	2000	1999	2000	1999	2000	2000	2001	2000	2001	2000	2001	2000	2001
St -1	Max	0.83	1.52	1.86	2.21	1.23	1.73	0.84	5.51	1.35	2.18	2.09	3.96	1.59	3.89
	Mean	0.51	1.01	0.89	1.01	0.90	1.29	0.59	1.67	0.58	1.09	0.69	1.76	0.53	1.62
St -2	Max	0.74	0.83	*1.72	1.49	1.05	1.48	0.90	4.18	0.83	1.87	1.31	3.98	3.71	4.38
	Mean	0.46	0.49	0.69	0.79	0.69	0.99	0.46	1.47	0.40	0.79	0.48	1.74	0.98	1.40
St -3	Max	0.67	1.03	*2.05	1.60	1.55	1.66	1.29	3.57	1.21	1.44	2.28	4.21	3.52	5.92
	Mean	0.43	0.53	0.82	1.00	0.98	1.15	0.66	1.11	0.83	0.89	0.79	1.77	1.21	1.45
St -4	Max	*1.13	1.00	1.28	1.37	1.02	1.10	0.77	2.78	1.26	1.32	1.92	3.08	2.35	4.97
	Mean	0.52	0.56	0.70	0.75	0.68	0.80	0.53	1.08	0.66	0.68	0.69	1.55	0.92	1.58

Table 6. Monthly mean and maximum PM_{10} concentrations (mg m^{-3}) from June 2000 to May 2001.

Month	6	7	8	9	10	11	12	1	2	3	4	5
Mean	0.20	0.17	0.15	0.15	0.20	0.30	0.35	0.49	0.32	0.39	0.45	0.18
Max	0.89	0.57	0.28	0.33	0.34	0.72	0.56	2.56	1.23	1.12	1.54	0.47

Table 7. API and air quality management in China.

Air Pollution Index	Air Quality Classification		Air Quality Description and Management
API $\leq$ 50	I	Clean	No action is needed.
50 < API $\leq$ 100	II	Good	No action is needed.
100 < API $\leq$150	III_1	Low-level pollution	Persons should be careful in outdoor activities.
150 < API $\leq$200	III_2		
200 < API$\leq$ 250	IV_1	Mid-level pollution	Persons with existing heart or respiratory illnesses are advised to reduce physical exertion and outdoor activities.
250 < API$\leq$ 300	IV_2		
API $\geq$300	V	High-level pollution	Air pollution is severe; The general public is advised to reduce physical exertion and outdoor activities.

Table 8. Monthly mean, maximum, and minimum API of TSP in March 2001.

	St-1 TSP	St-2 TSP	St-3 TSP	St-4 TSP	St-5 TSP	St-6 TSP	St-7 TSP	St-8 TSP
Max	>500	>500	>500	>500	>500	>500	>500	>500
Min	359	346	209	306	87	238	365	365
Mean	>500	>500	>500	>500	400	>500	>500	>500

Table 9. Monthly mean and maximum API of PM_{10} from June 2000 to May 2001.

Month	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
Mean	134	115	102	101	126	206	255	276	210	264	294	118
Max	>500	467	160	192	197	>500	464	>500	>500	>500	>500	356

Table 10. TSP observational days, the days with the API of TSP between 201 to 300 and greater than 300 during a month, and the occurrence rate of severe TSP alert, which is the ratio between the days with API of TSP greater than 200 and the total days of observation. The symbol '-' is referred to no-observational data.

Observational Station	District	Year	1999			2000												2001			
		Month	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
		Days	13	14	13	13	13	13	12	14	13	13	13	13	14	12	13	14	12	13	12
#1	Chengguan (Dist-1)	201-300	3	0	2	1	4	3	1	6	0	2	2	2	1	0	1	0	2	0	0
		> 300	4	11	11	3	4	6	3	4	0	3	3	9	12	10	11	14	9	13	11
		Total	7	11	13	4	8	9	4	10	0	5	5	11	13	10	12	14	11	13	11
		Rate(%)	54	79	100	46	62	69	33	71	0	38	38	85	93	83	92	100	92	100	92
#2	Chengguan (Dist-1)	201-300	2	2	2	0	0	1	3	4	2	2	1	1	2	1	0	4	3	0	1
		> 300	3	6	7	3	2	2	6	7	3	0	0	3	5	7	12	9	6	13	9
		Total	5	8	9	3	2	3	9	11	5	2	1	4	7	8	12	13	9	13	10
		Rate(%)	39	57	69	23	15	23	75	79	38	15	8	31	50	67	92	93	75	100	83
#3	Qilihe (Dist-2)	201-300	3	4	0	1	2	1	2	4	3	0	0	2	4	1	0	2	1	1	1
		> 300	2	8	13	8	10	5	7	9	8	1	0	4	4	11	13	10	10	12	9
		Total	5	12	13	9	12	6	9	13	11	1	0	6	8	12	13	12	11	13	10
		Rate(%)	38	86	100	69	92	46	75	93	85	8	0	46	57	100	100	86	92	100	83
#4	Xigu (Dist-3)	201-300	1	1	4	0	1	2	3	2	3	2	2	2	3	2	1	1	4	0	1
		> 300	4	9	8	5	8	5	5	11	4	5	6	6	5	7	10	12	6	13	9
		Total	5	10	12	5	9	7	8	13	7	7	8	8	8	9	11	13	10	13	10
		Rate(%)	38	71	92	38	69	54	67	93	54	54	62	62	57	75	85	93	83	100	83
#5	Yuzhong (background)	201-300	0	1	0	0	2	1	1	4	1	1	0	0	1	0	1	0	0	2	1
		> 300	0	0	0	0	0	2	4	2	0	0	0	1	0	1	3	3	3	7	5
		Total	0	1	0	0	2	3	5	6	1	1	0	1	1	1	4	3	3	9	6
		Rate(%)	0	7	0	0	15	23	42	43	8	8	0	8	7	8	31	21	25	69	50
#6	Chengguan (Dist-1)	201-300	-	-	-	-	-	-	-	-	-	-	1	5	1	1	0	2	2	1	1
		> 300	-	-	-	-	-	-	-	-	-	-	0	2	5	9	10	8	6	12	9
		Total	-	-	-	-	-	-	-	-	-	-	1	7	6	10	10	10	8	13	10
		Rate(%)	-	-	-	-	-	-	-	-		-	8	54	43	83	77	71	67	100	83
#7	Anning (Dist-4)	201-300	-	-	-	-	-	-	-	-	-	-	0	2	4	2	2	4	2	0	0
		> 300	-	-	-	-	-	-	-	-		-	0	4	3	5	8	7	4	13	10
		Total	-	-	-	-	-	-	-	-	-	-	0	6	7	7	10	11	6	13	10
		Rate(%)	-	-	-	-	-	-	-	-	-	-	0	46	50	58	77	79	50	100	83
#8	Xigu (Dist-3)	201-300	-	-	-	-	-	-	-	-	-	-	1	2	2	3	2	1	0	0	1
		> 300	-	-	-	-	-	-	-	-	-	-	0	3	5	6	6	11	7	12	9
		Total	-	-	-	-	-	-	-	-	-	-	1	5	7	9	8	12	7	12	10
		Rate(%)	-	-	-	-	-	-	-	-	-	-	8	38	50	75	62	86	58	92	83

Table 11. Occurrence rate (%) of different levels of TSP pollution.

Season	spring (331 observational days)	summer (195 observational days)	fall (381 observational days)	winter (429 observational days)
API > 300	68	16	45	63
300 ≥ API > 200	11	11	15	13
200 ≥ API > 150	11	20	13	12
150 ≥ API > 100	5	26	14	7

Table 12. Occurrence rate (%) of different levels of PM_{10} pollution.

Season	spring (92 observational days)	summer (88 observational days)	fall (91 observational days)	winter (90 observational days)
API > 300	25	1	8	32
300 ≥ API > 200	10	0	4	10
200 ≥ API > 150	22	7	22	25
150 ≥ API > 100	22	45	30	22

Table 13. Dust storm statistics in Gansu Province from December 2000 to April 2001.

Occurring time	Wind velocity ($m.s^{-1}$)	Least visibility	Scope of dust storms
12/31/2000- 1/1/2001	14-20, Max:23	< 100 m	Dust storms in Jinta, Dingxing, Minqin, flying dust and flying ashes in other parts of Hexi and its eastern region
1/11/2001 - 1/12/2001	12-17, Max: 22	< 200 m	Dust storms in Jinta, Dingxing, Zhangye, Linze, Gaotai, Minqin, Yongchang , flying dust and flying ashes in other parts of Hexi and its eastern region
1/30/2001	11-19, Max: 22	< 80 m	Dust storms in Jiuquan, Jinta, Gaotai, Yongchang, Guaizihu[1] Wudaoliang[2] ,Taole[3] etc, flying dust and flying ashes in other parts of Hexi and its eastern region
2/16/2001	10-15	250 m	Dust storms in Guannan[2] ,Maqu
2/23/2001	10-14	8 m	Dust storms in Dunhuang ,Anxi
3/4/2001 -3/5/2001	14-20, Max: 24	< 100 m	Dust storms in Jiuquan, Dunhuang, Jinta, Dingxin, Minqin, Guaizihu[1], Bayanmaodao[1], Gangcha[2], Menyuan[2], Gonghe[2], Guannan[2] etc, flying dust and flying ashes in other parts of Hexi and its eastern region
3/13/2001	12-17	16 m	Dust storms in Guaizihu[1], Etuokeqi[1], Taole[3]
3/26/2001	11-15, Max: 19	< 60 m	Dust storms in Dingxin,Wuwei, Jinchang, Shandan, Jintai, Guaizihu[1] etc, flying dust and flying ashes in other parts of Hexi and its eastern region
4/6/2001 -4/8/2001	12-20, Max: 23	0m	Dust storms in Dunhuang ,Mazongshan, Dingxin, Jinta, Jiuquan, Zhangye, Linze, Gaotai, Shandan, Jinchang, Yongchang, Minqin, Wuwei, Gulang,Wushaoling, Jingyuan, Jingtai, Baiying, Yongdong, Lanzhou, Hezheng, Linxia, Huanxian, Pingliang, Huajialing, Dingxi, Xining[2], Wulan[2], Dulan[2],Wudaoliang[2] etc, flying dust and flying ashes in other parts of Gansu
4/12/2001	10-15, Max: 20	< 10 m	Dust storms in Minqin, Wuwei, Jingtai, Wushaoling, flying dust and flying ashes in other parts of Hexi and its eastern region
4/19/2001	10-15	4m	Dust storms in Dunhuang, Zhangye, Gaotai, Jintai
4/28/2001 -4/29/2001	15-20, Max: 23	0m	Dust storms in Dunhuang, Anxi, Yumen, Gaotai, Zhangye, Jinta, Jiuquan, Dingxing, Yongchang, Minqin, Jinchang, Baiyin, Jingtai, Yuzhong, Gaolan, Huining, Huajialing, flying dust and flying ashes in other parts of Hexi and its eastern region

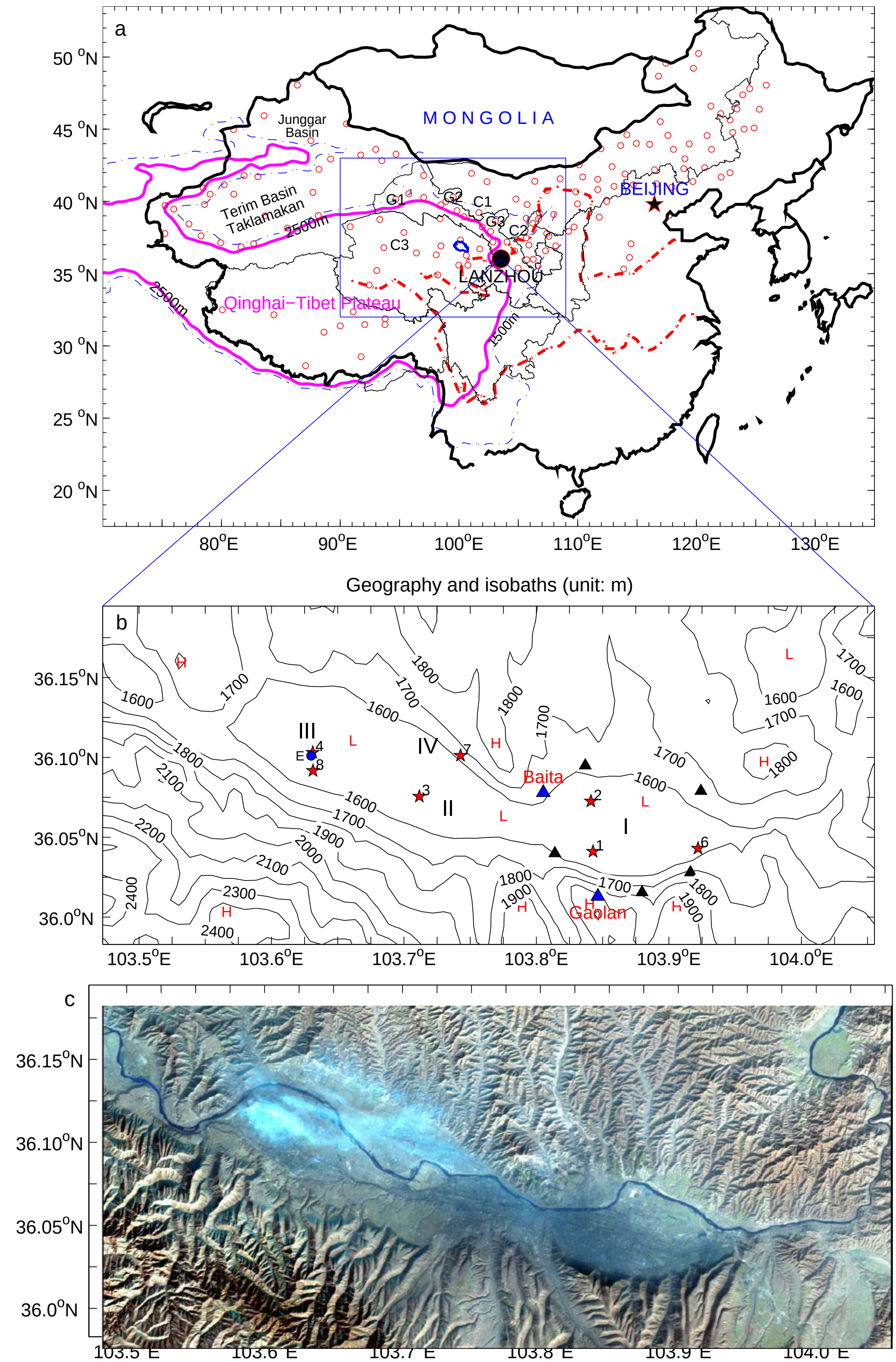

Figure 1: Lanzhou: (a) geography, (b) topography, and (c) LANDSAT-TM imagery representing air pollution on 3 January 2001.

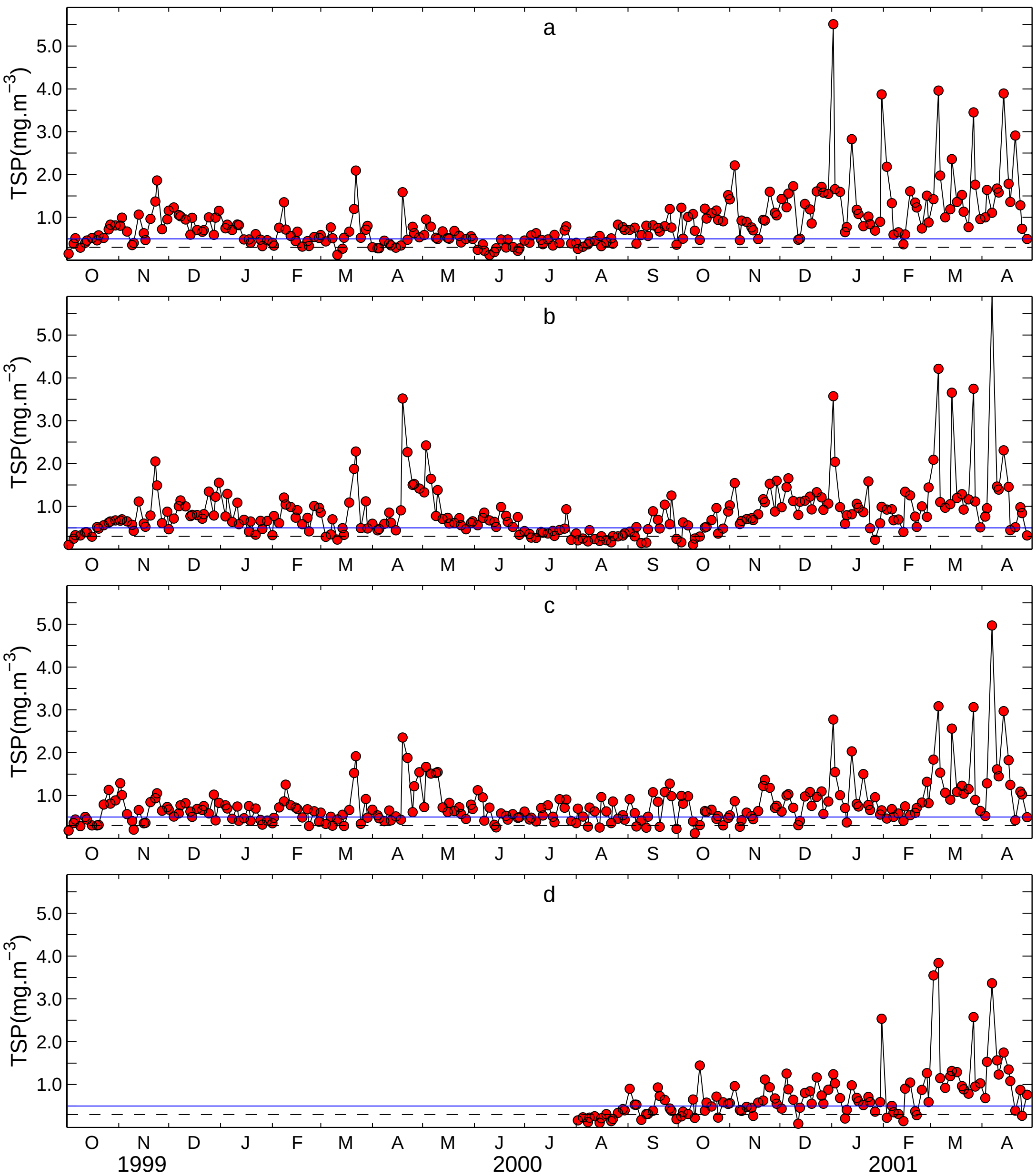

Figure 2. Daily mean TSP concentrations (mg m^{-3}) at: (a) St-1 (District-I), (b) St-3 (District-II), (c) St-4 (District-III), and (d) St-7 (District-IV)). Horizontal dashed line is daily mean second-level criterion (0.2 mg m^{-3}), while horizontal solid line is daily mean third-level criterion. Note that the daily mean TSP concentration is usually above the second-level criterion (0.3 mg m^{-3}).

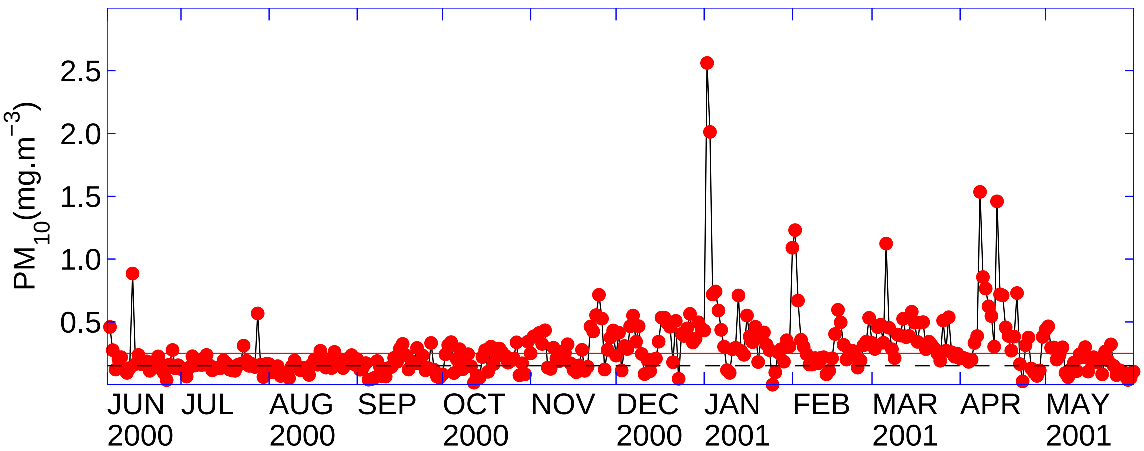

Figure 3. Daily mean PM_{10} concentration at station-E. Horizontal dashed line is the daily mean second-level criterion (0.2 mg m^{-3}), while horizontal solid line is the daily mean third-level criterion (0.3 mg m^{-3}).

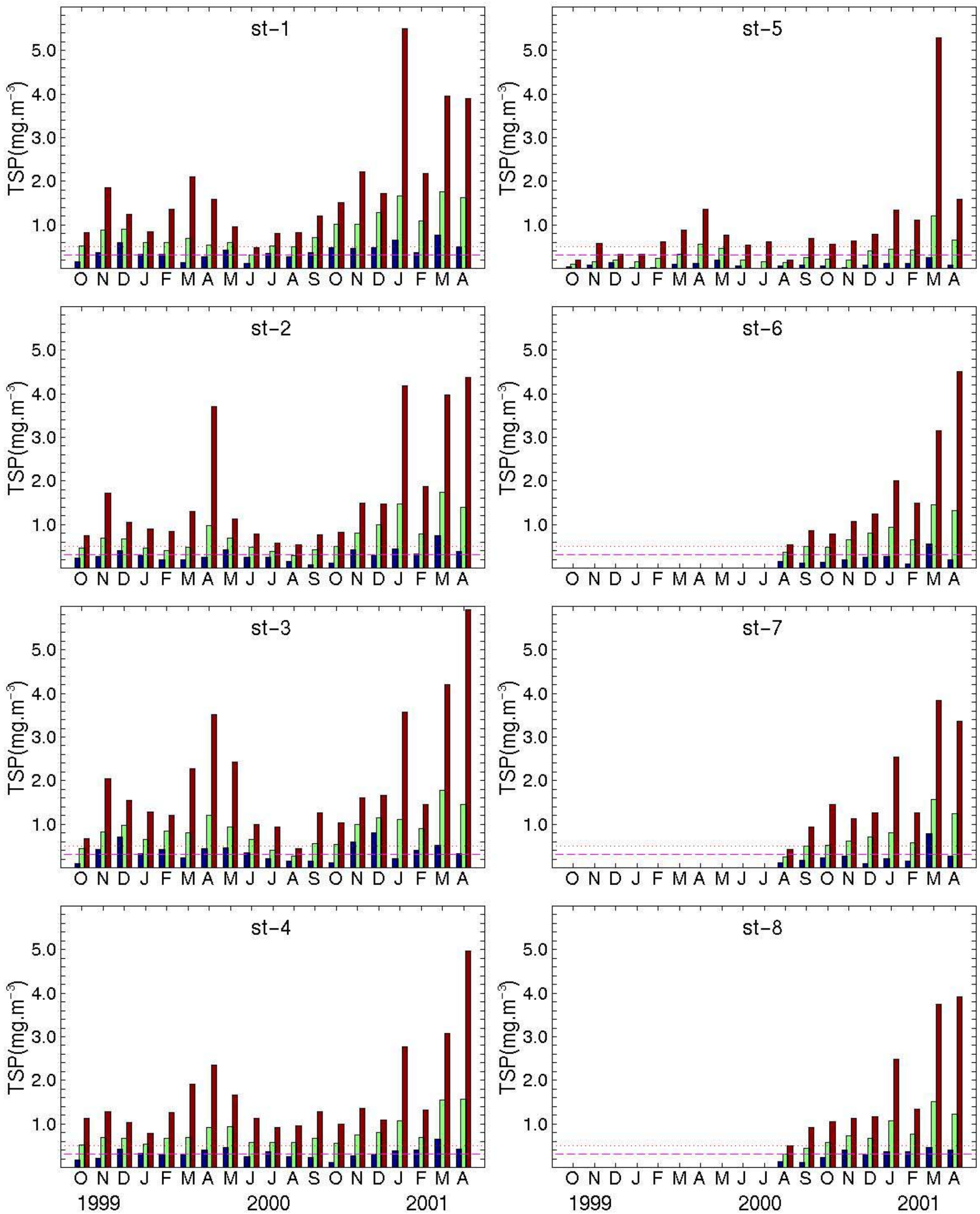

Figure 4. Monthly mean, maximum, and minimum TSP concentrations (mg m^{-3}) at St-1 to St-8.

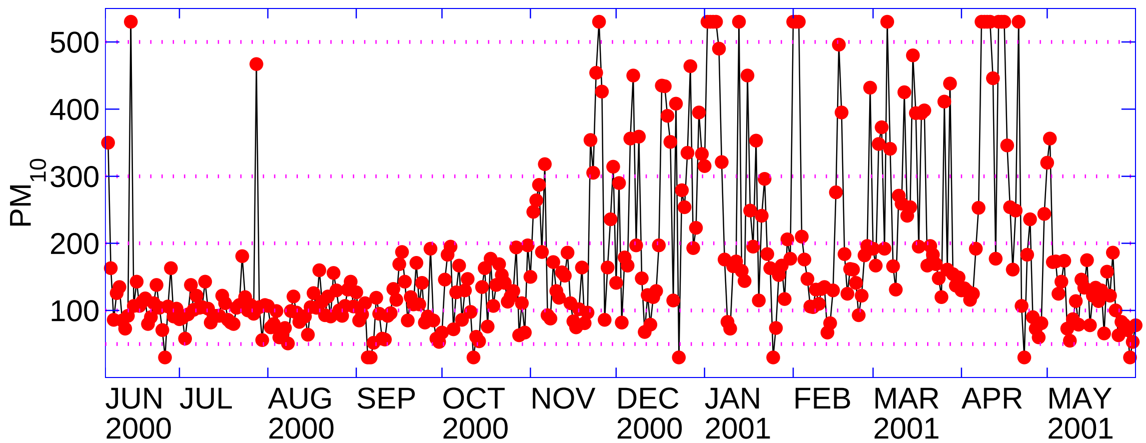

Figure 5. Daily mean API of PM_{10} at station-E.

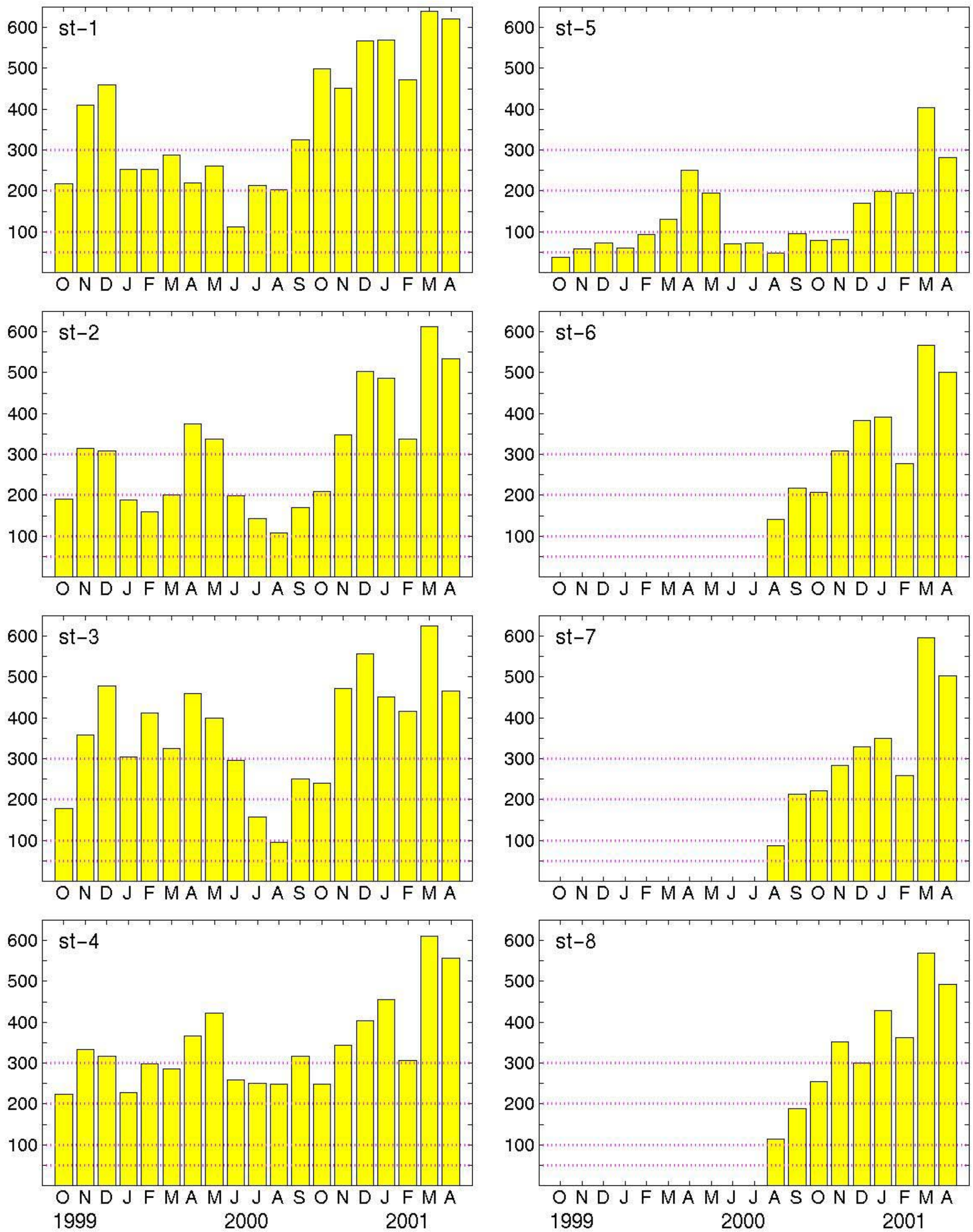

Figure 6. Monthly mean API of TSP at St-1 to St-8.

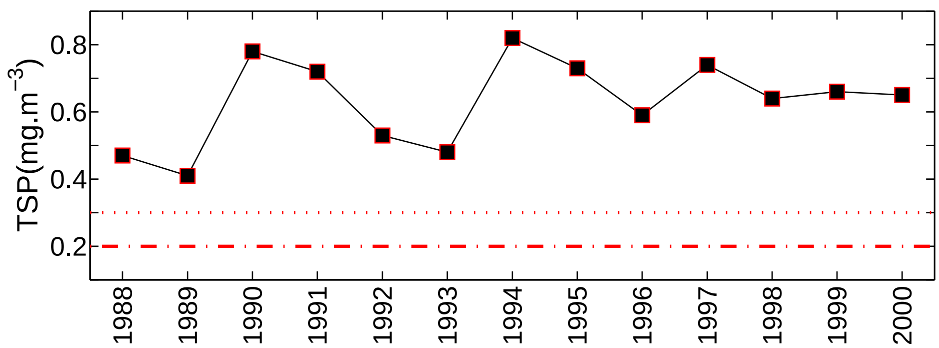

Figure 7. Annual mean TSP concentration (mg m^{-3}) measured at the SEPA station (103.631^{o}E, 36.103^{o}N), which is marked as the solid circle in Fig. 1b. The second-level criterion (0.2 mg m^{-3}) is represented by the horizontal dash-dotted line and the third-level criterion (0.3 mg m^{-3}) is represented by the horizontal dotted line.

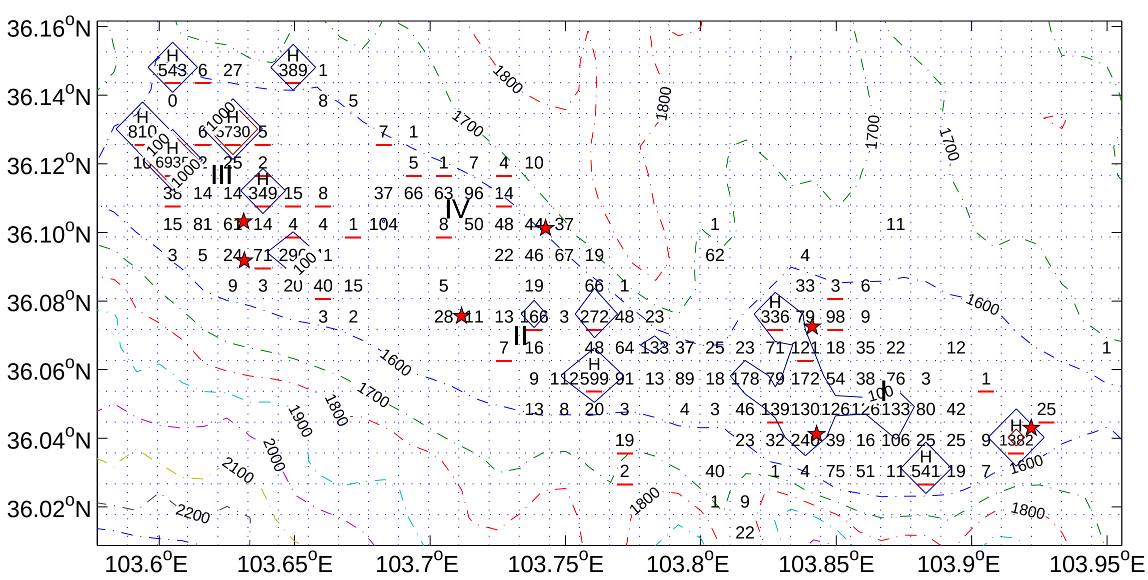

Figure 8. Spatial distribution of annual particulate pollutant emission rate per square kilometer (unit: 0.1×10^{4} kg km^{-2} yr^{-1}) in 2000. Here, the industrial sources are indicated with underlines; high-level sources are represented by the enclosed solid curves marked as ‘H’. The dashed contours are topography (unit: m).

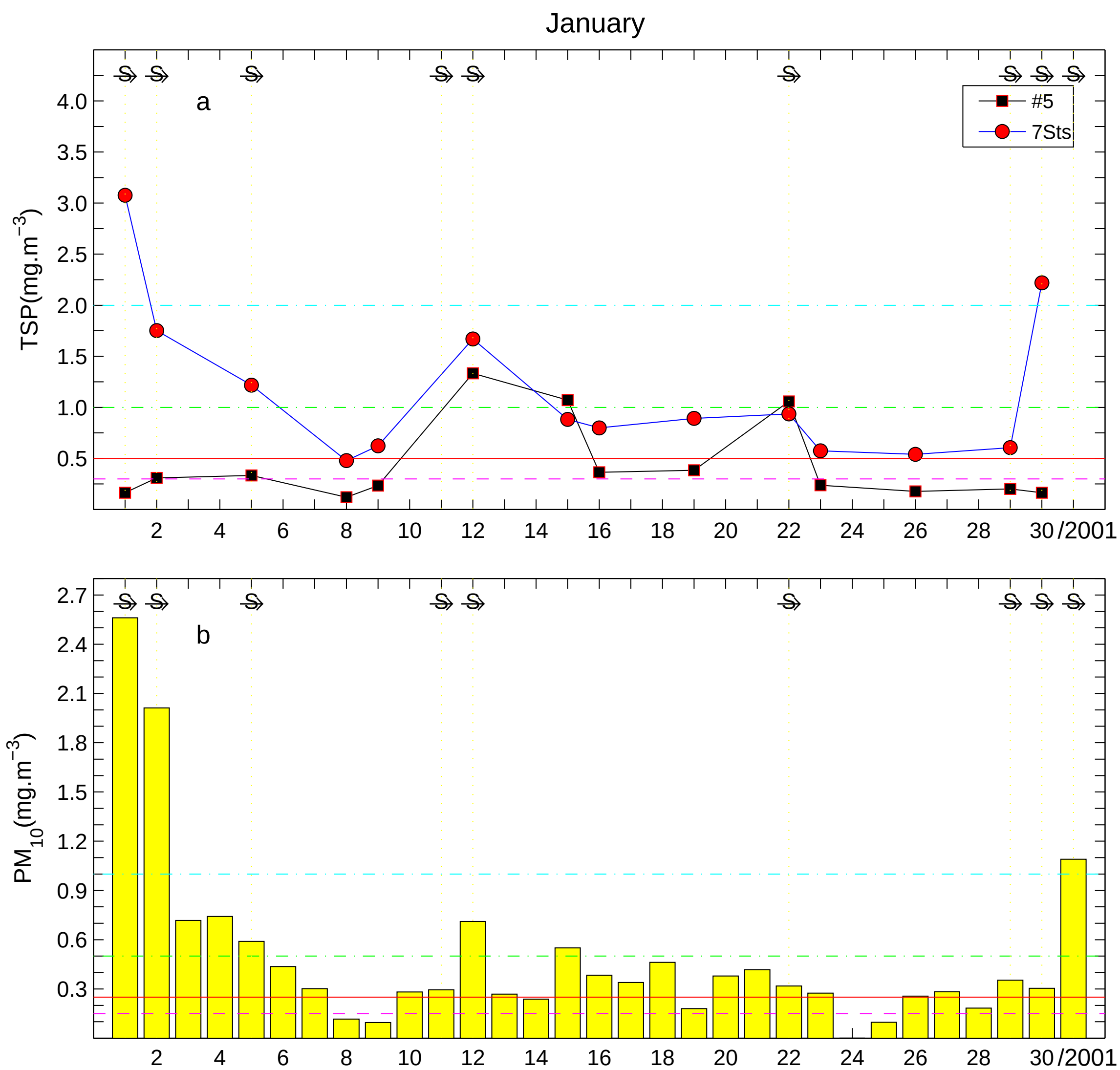

Figure 9. Daily mean (a) TSP, (b) PM_{10} concentrations (dust storm represented by the symbol '') in January 2001.

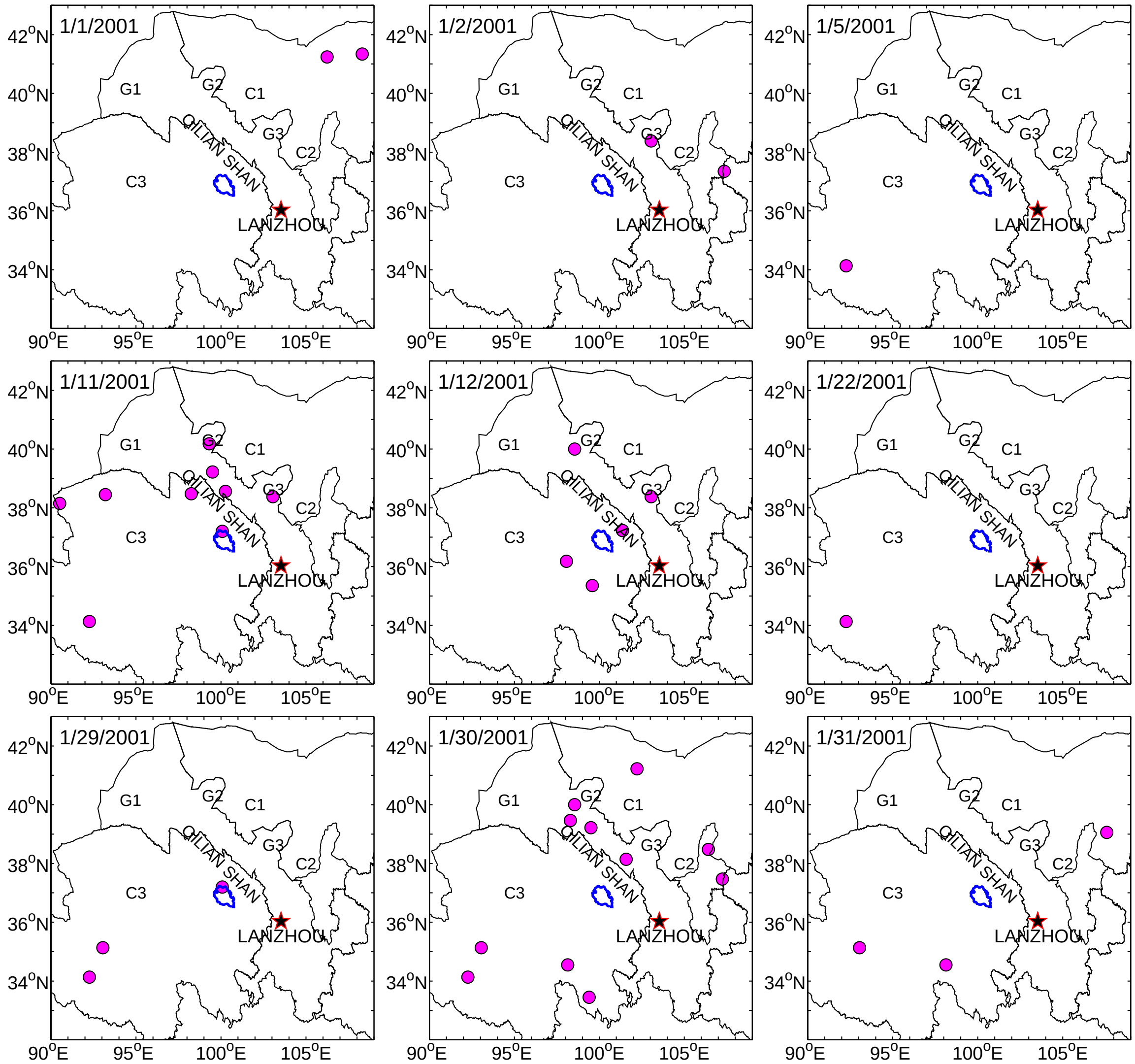

Figure 9c. Horizontal distribution of dust storms (solid dots) in January 2001.

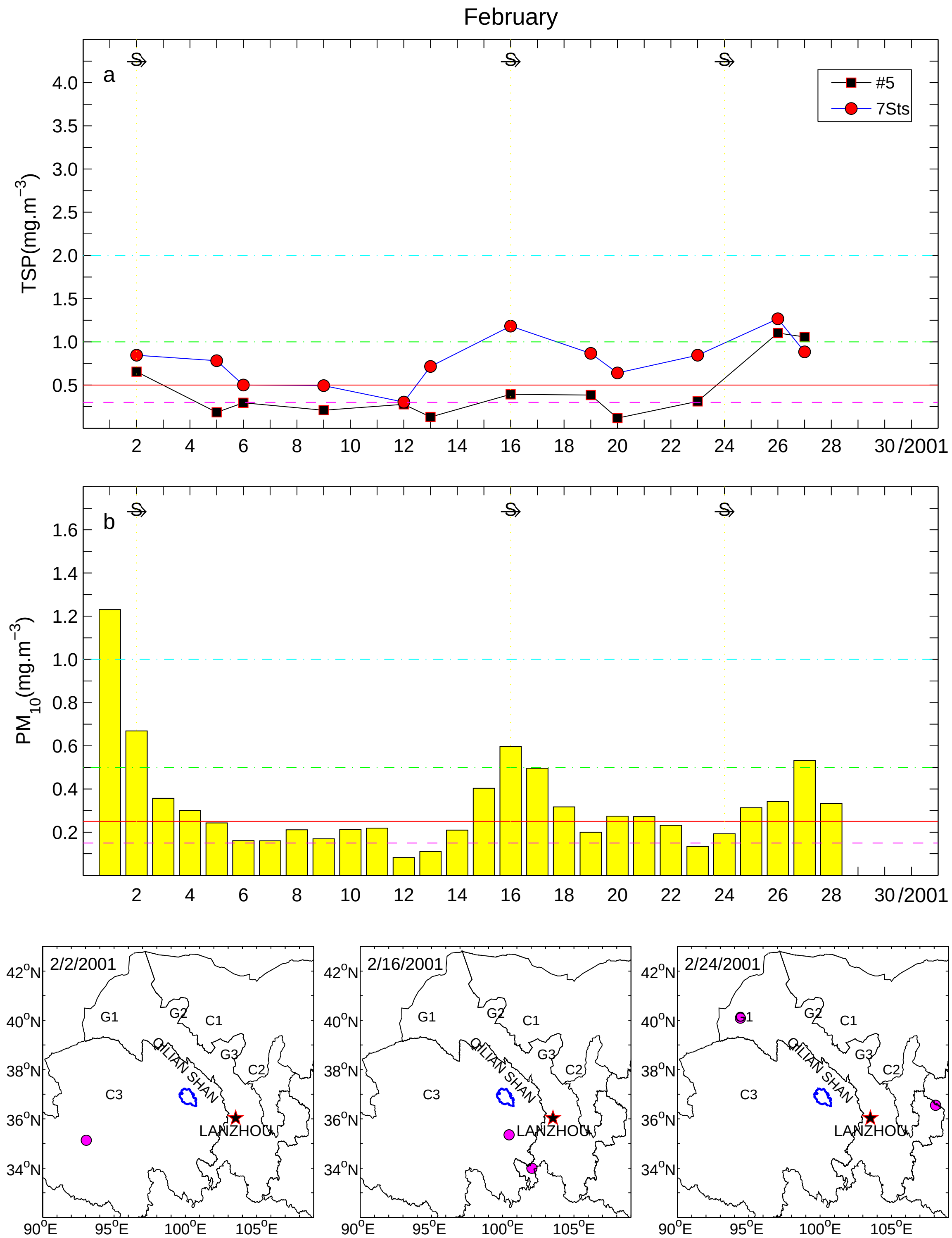

Figure 10. Same as Figure 9 except for February 2001.

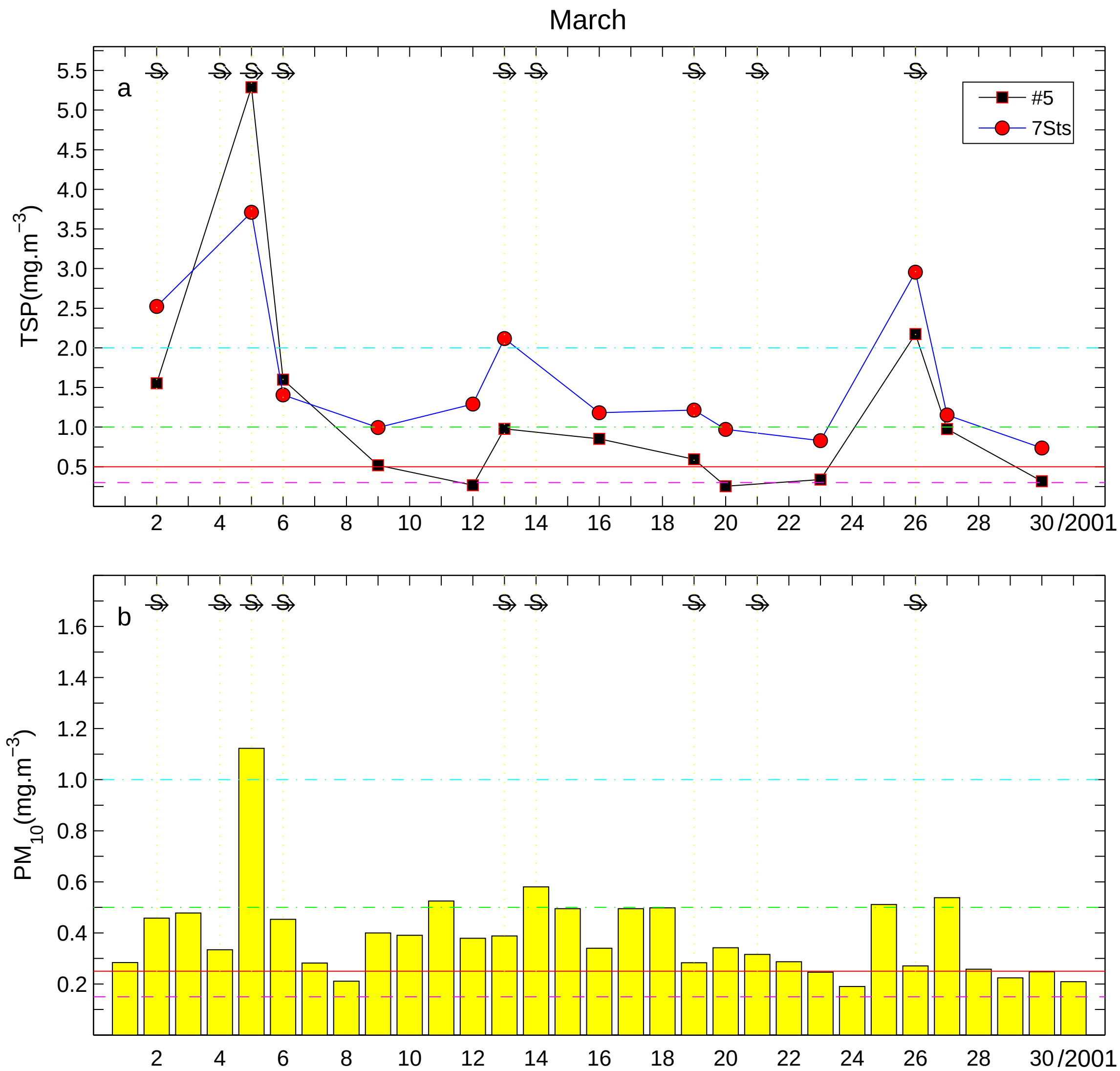

Figure 11a, b. Same as Figure 9a, b except for March 2001.

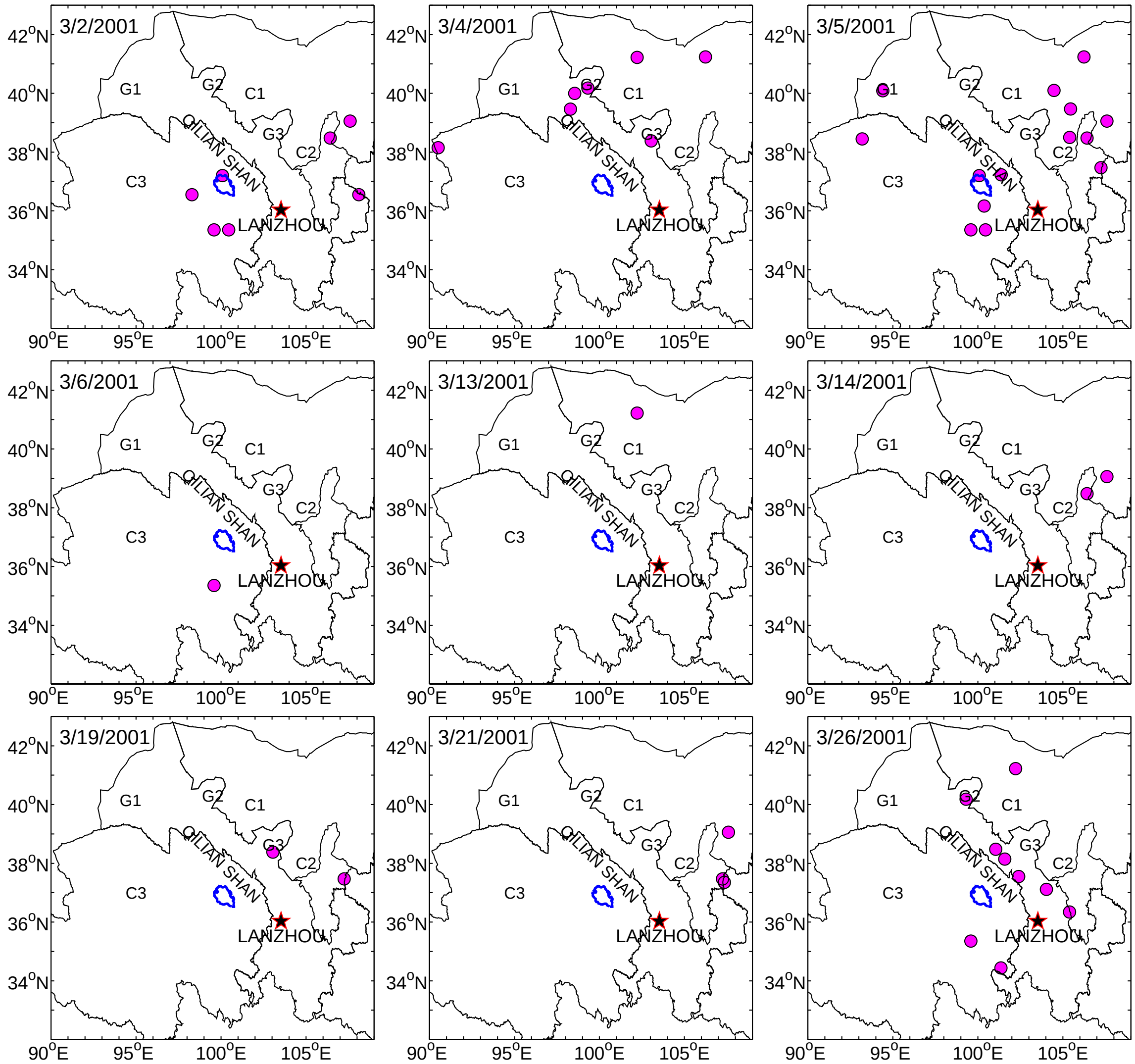

Figure 11c. Same as Figure 9c except for March 2001.

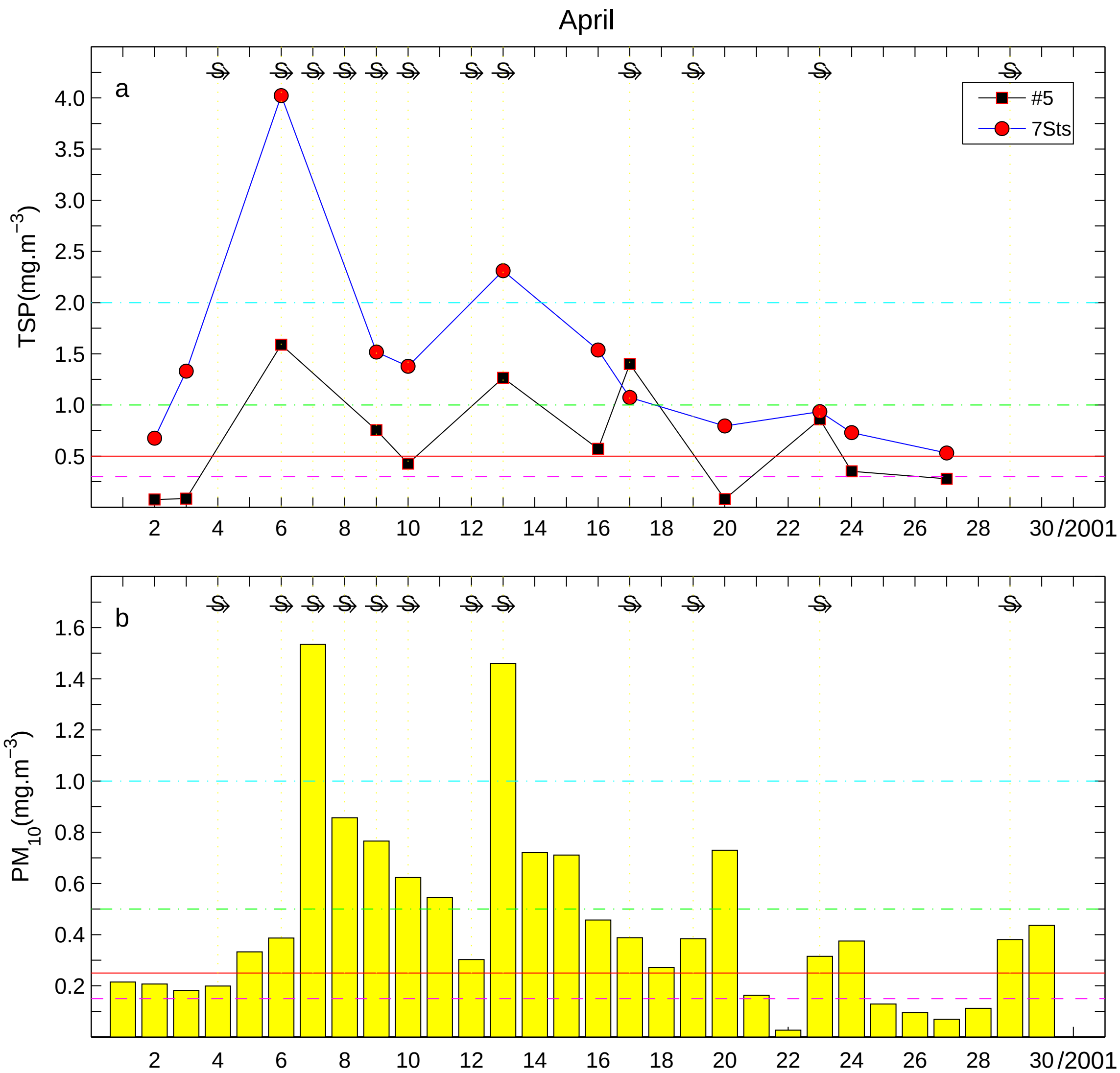

Figure 12 a, b. Same as Figure 9 a, b except for April 2001.

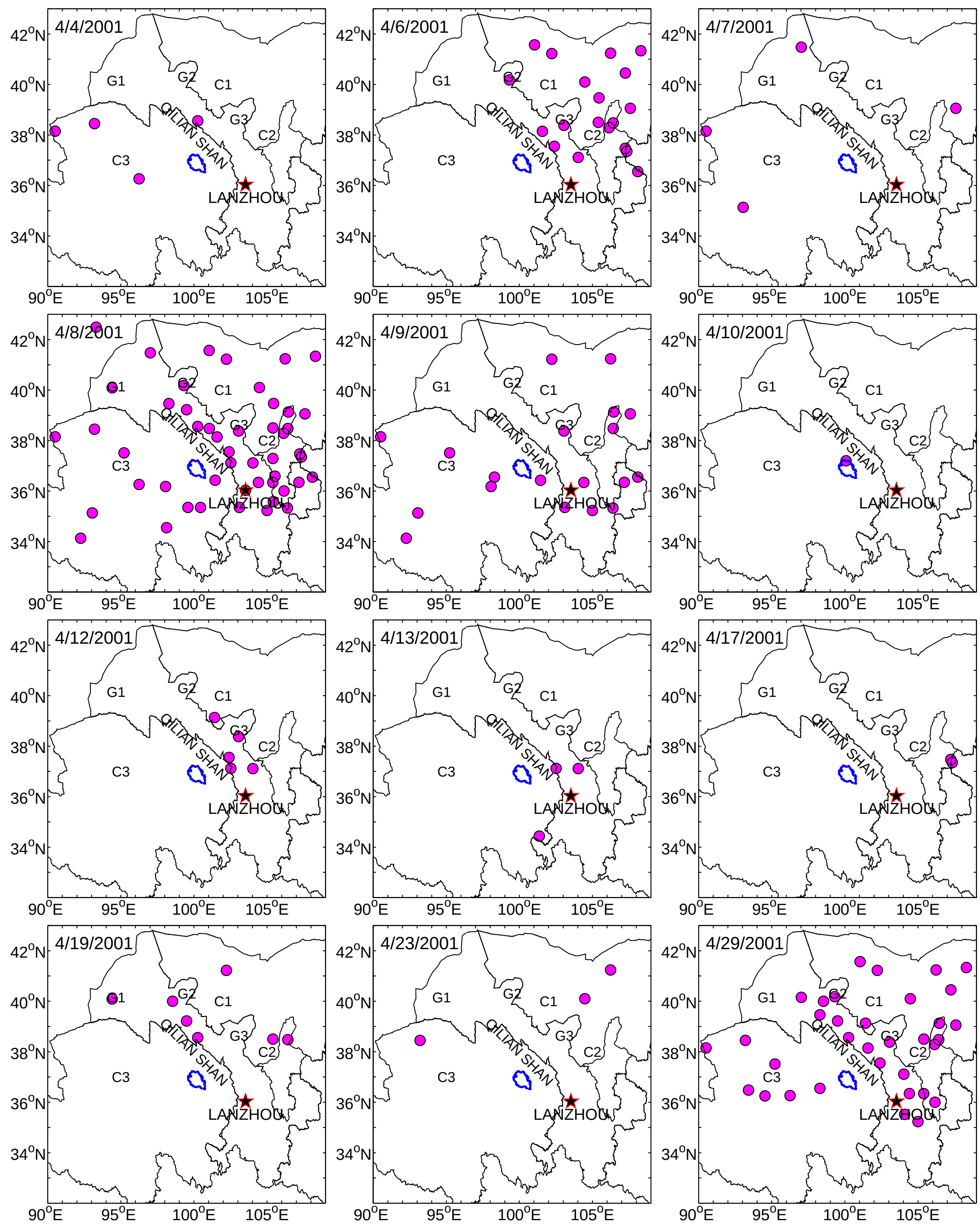

Figure 12c. Same as Figure 9c except for April 2001.